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Life Cycle Assessment of Environmental Systems: A Review of Methodologies, Applications, and Future Directions

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Abstract

Life Cycle Assessment has become central to evaluating environmental systems. With growing climate and resource pressures, LCA is now applied beyond products to energy, water, waste, and urban systems, yet methodological variability affects consistency and policy relevance. This review aimed at examining LCA methodologies, mapping current applications to environmental systems, and identifying challenges and future directions for improved decision support. Findings from this study revealed that methodological advances include wider adoption of consequential and hybrid LCA, dynamic modelling, regionalized inventories, and uncertainty analysis. Database harmonisation and open LCA platforms have improved data accessibility, though foreground data gaps persist. In impact assessment, there is progress toward ecosystem services, toxicity, and planetary boundary metrics. Application-wise, LCA is extensively used for renewable energy systems, carbon capture, water and wastewater treatment, agriculture, and built environments to inform eco-design and policy instruments like EPDs and carbon labels. Case studies show LCA supports technology comparison and circular economy strategies. However, inconsistencies in system boundaries, allocation, and temporal considerations limit comparability. Emerging integrations with AI, process simulation, and digital twins enable near real-time assessment, while prospective LCA is gaining traction for novel technologies. Standardisation and transparency remain key barriers. LCA is evolving from static product assessment to a dynamic systems tool for environmental decision-making. Future progress depends on methodological harmonisation, higher quality and open data, and integration with AI and policy frameworks. Strengthening these areas will enhance LCA's role in guiding sustainable design, circularity, and net-zero transitions across environmental systems.

Keywords: *Life cycle assessment, Circular economy, Resource conservation, Dynamic LCA, and Digital twins.*

Introduction

Under the new tracking mechanisms of contemporary macro-ecological systems, there exist major anthropogenic disruptions that pose challenges to the equilibrium of the existing ecological systems [1]. These include industrial activities, intense agricultural practices and rising levels of consumption resulting in the buildup of greenhouse gases in the atmosphere, biodiversity loss and ecosystem toxicity [2]. The solution to such challenges involves diagnostic tools to map out how resources are extracted, processed and consumed and their impacts on the regional and global biospheres [3,4]. In the past, environmental regulations and industrial management strategies used isolated and local approaches where end-of-pipe control of pollutants was employed [5]. Localised methods of managing environmental disruption were often accompanied by unintended burden shifting from one geographic zone to another, medium and life cycle phase [6, 7].

In order to achieve environmental sustainability in a global perspective, it calls for a paradigm change in science towards a multi-dimensional approach where industrial systems are viewed as complex metabolic systems limited by the planet [8,9]. As articulated in macro-economic circularity models, at the heart of this transformation towards sustainability lies the conception and implementation of the circular economy [1]. The circular economy denotes a new macro-economic model specifically designed to separate economic growth from the exploitation of non-renewable natural resources and environmental degradation [1]. Contrary to the traditional extractive "take-make-waste" approach, the circular economy aims to optimize value retention, product durability, and the perpetual cycling of materials and goods in closed loops [3, 4]. As conceptualized in this framework, structural waste does not represent an end state but a valuable source of secondary resources or byproducts intended to be used in cascades in industry chains [5,6].

This transformation can only be implemented through the application of quantified metrics that prove the positive impact of these closed-loop loops on the environment and not just increase energy consumption and chemicals in the recycling phase [7]. Consequently, a deep operational alignment must be forged between the holistic philosophy of the circular economy and the highly standardised, mathematical frameworks of life cycle thinking to ensure that circular designs translate into authentic ecological relief [1, 8].

In recent assessments of global resource boundaries, the connection underscores the importance of resource conservation in maintaining the ecological integrity of the planet [4]. Resources that include biotic systems, mineral sources, waters, and funds are located at the critical boundary point where the natural world and human industry meet [5]. Within a linear production approach, the increasing consumption of raw materials takes away the environmental ability to supply what is needed while disrupting crucial ecological support functions of our planet [6]. Resource conservation requires not only reducing the rate of resource use but also optimising the material use, implementing non-fossil alternative feedstocks, and applying design for recyclability approaches within complex multi-material product structures [7]. Measuring the effectiveness of resource conservation measures necessitates the calculation of all physical activities within the value chain in order to ensure that any primary material savings during one stage of the cycle do not increase energy use or toxicity elsewhere [8].

As per standardised structural literature, Life Cycle Assessment (LCA) acts as the sole scientific approach and decision-making framework that enables this comprehensive and systemic accounting [9]. Internationally standardised as per ISO 14040 and 14044, LCA analyses the environmental performance of a process, product or system through a well-defined four-stage structure – goal and scope definition, life cycle inventory analysis, life cycle impact assessment and interpretation [10, 11]. Through this holistic analytical approach, LCA systematically accounts for the entire life span history of an environmental system in terms of its material and energy flows from its origin-based cradle-to-grave or cradle-to-cradle routes [12, 13]. LCA provides the empirical basis for eco-design, industrial supply chain management and sustainable business reporting through the conversion of complicated data of raw input materials, transportation needs, chemical processing variables and emission vectors into a detailed set of multi-dimensional environmental impacts [14, 15]. With the growing complexity of industrial and environmental systems due to digitalisation and bio-refineries, the implementation of LCA becomes inevitable to reveal environmental trade-offs and shape multi-party strategic policies [16].

As pointed out in recent literature, while there has been a rapid increase in life cycle literature, modern-day reviews are often restricted by an isolated approach, examining only one particular industrial domain, geographic location, or software update [17]. These specialised studies rarely address the bigger picture and systemic mechanisms behind structural environmental change, thus creating a significant disconnect between evaluative analysis and transformative policies [18].

The principal objective of this review is to help bridge this gap through the synthesis of broader methodological developments, specific applications in different sectors, as well as future research opportunities that define the Life Cycle Assessment of environmental and industrial systems. Through the examination of the connection between lifecycle analysis and real-world objectives of the circular economy and resource conservation, the present paper identifies current strengths and weaknesses of LCA, its structural inventory limitations, and its ability to become a catalyst for environmental change. Lastly, this review outlines a clear plan for future research in the field.

Principles and Methodological Framework of Life Cycle Assessment

Life Cycle Thinking

To transition from localised environmental compliance toward global environmental sustainability, industrial and ecological systems must be evaluated using life cycle thinking [19]. This paradigm expanded beyond reactive environmental troubleshooting by requiring an exhaustive assessment of material and energy flows at every phase of a product or process history [20]. Rather than restricting analysis to factory gates or localised production sites, life cycle thinking traces the upstream raw material extractions and downstream waste management stages that define the ultimate footprint of human enterprise [21]. This holistic oversight is critical to identifying and preventing environmental burden-shifting, an operational failure where mitigating an environmental problem in one processing step inadvertently increases ecological damage in another [22].

Central to this structural mapping is the strict demarcation of system boundaries, which establish the analytical limits of what is included in the life cycle model. The three most prevalent system boundaries deployed in contemporary assessments include cradle-to-grave, cradle-to-gate, and cradle-to-cradle frameworks [23]. A cradle-to-grave boundary establishes a comprehensive path, tracking a product from its initial resource extraction through manufacturing, logistics, and user phases, culminating in its final disposal or incineration [24]. In contrast, a cradle-to-gate boundary acts as a partial assessment, truncating the scope once a product leaves the manufacturing plant, making it ideal for business-to-business raw material assessments where subsequent end-use configurations vary widely [25]. Finally, the cradle-to-cradle framework models an advanced circular paradigm where the end-of-life stage is explicitly closed, transforming what would traditionally be considered landfill waste into high-value secondary inputs for subsequent manufacturing cascades [26]. The interactions of these processing loops are illustrated in Figure 1.

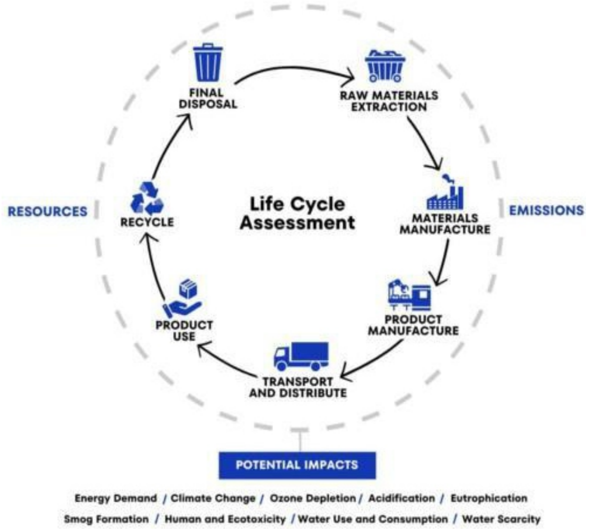

Figure 1. Life cycle thinking in environmental systems

Source: [23]

Integrating system boundaries directly within the operational architecture allows investigators to isolate critical hot spots within complicated distribution networks [24]. When evaluating product pathways under a cradle-to-grave scope, the inclusion of the use and disposal phases frequently reshapes the overall impact profile, shifting the primary environmental burdens from factory energy use to consumer habits or post-consumer municipal waste management [27]. Conversely, utilising a cradle-to-gate framework places the analytical focus squarely on resource extraction efficiencies, supply-chain transport, and core refining technologies [5]. In systems oriented around the circular economy, executing a cradle-to-cradle boundary introduces sophisticated multi-functional allocation problems, as the environmental burdens of the original material extraction must be shared or partitioned across multiple consecutive use-cycles [28]. Ultimately, the selection of these boundaries dictates the configuration of the life cycle inventory, dictating which resource inflows and emissions outflows are tracked against the baseline environmental system [29].

ISO 14040/14044 Framework

To maintain scientific accuracy and allow cross-comparison across global supply chains, Life Cycle Assessments should strictly adhere to the internationally standardised architectures set forth by the International Organisation for Standardisation ISO 14040 and 14044) [22]. The internationally recognised system splits the complicated process of environmental assessment into an iterative four-step process [21]. Since life cycle systems are inherently dynamic, the four steps do not follow each other sequentially but rather create a complex interconnected iterative cycle, wherein the findings at subsequent steps prompt reevaluation of the initial parameters of the model [30]. In addition, modern advancements in industry tracking, like IoT sensors and digital twins, have enabled these four steps to be integrated, thus allowing for life cycle model adjustments in real time [24]. The organisation of the structure of this standardised procedure is shown in Figure 2.

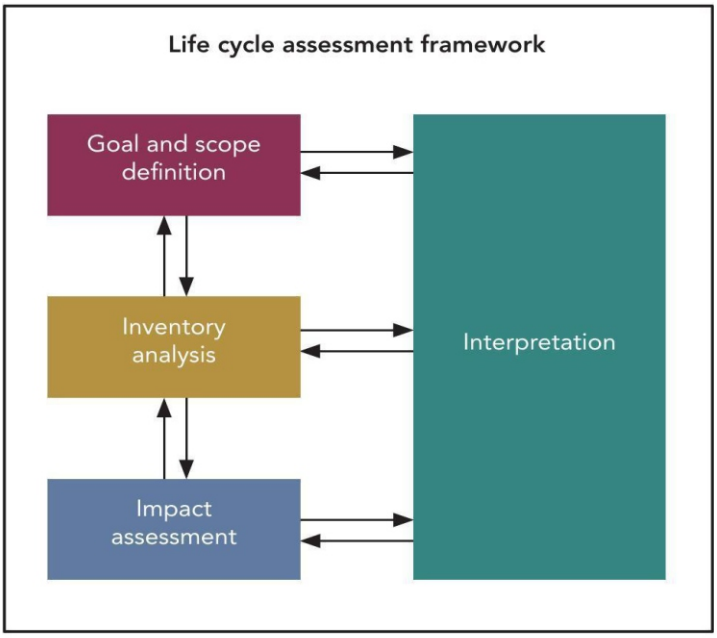

Figure 2. ISO life cycle assessment framework

Source: [29]

The goal and scope definition phase constitutes the basic starting point for the whole study, where the use and users of the system, along with its boundaries, are clearly defined [30]. Notably, at this stage, the Functional Unit is established; it represents a specific performance indicator that sets the scale against which all the inventory flows are measured [31]. Life Cycle Inventory (LCI) Phase is a phase of thorough data gathering and accounting process where experts make up the complete mass and energy balance for the specified system [32]. It involves the collection of basic raw data from industrial plants together with secondary data from worldwide databases, where each elementary flow, like fossil fuel extraction, water consumption, and emission of carbon dioxide and heavy metals into air and water bodies, is recorded. The third phase, Life Cycle Impact Assessment (LCIA), translates these vast LCI spreadsheets into clear environmental meaning. This is achieved by passing the inventory flows through characterised midpoint and endpoint models, sorting emissions into specific impact categories like global warming potential, terrestrial acidification, aquatic eutrophication, and human toxicity [33]. Finally, the Interpretation phase acts as the administrative and analytical conclusion of the framework [34]. In this phase, the findings from the LCI and LCIA are systematically evaluated through completeness checks, sensitivity analyses, and uncertainty iterations like Monte Carlo simulations [35]. This structured evaluation ensures that the resulting conclusions are robust, revealing clear environmental trade-offs and providing actionable data to guide corporate sustainability strategies, public policy, and eco-design redesigns [36].

Life Cycle Inventory and Impact Assessment

The execution of a life cycle assessment depends on constructing an empirical baseline during the inventory phase. Life Cycle Inventory (LCI) analysis acts as the core mathematical foundation of the study, demanding rigorous data collection and the tracking of all physical parameters across system boundaries [3]. Practitioners map out the complex paths of industrial metabolisms, logging every material flow and raw material input required to fulfil the chosen functional unit [12]. Concurrently, the process models account for all energy inputs, balancing electrical grid consumption, fuel burning, and thermal processes against output variables [37]. By tracking these resource demands alongside the resulting emissions released into atmospheric, aquatic, and terrestrial environments, the LCI phase builds a transparent, quantitative input-output model of the system [38].

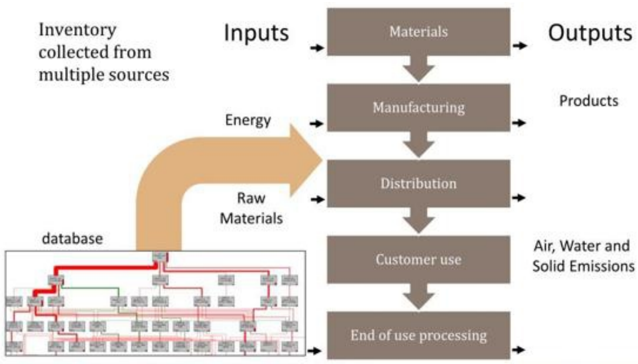

Figure 3. Workflow of life cycle inventory development

Source: [39]

As described in Figure 3. Workflow of Life Cycle Inventory Development," constructing an LCI model is an orderly and sequential process. The first step is System Definition, where boundary lines for the analysis are drawn in regard to the particular unit processes that are being analysed [4]. After setting up the boundaries, Data Collection commences by collecting primary data from industrial processes and linking it with secondary data from databases from the global background [39]. The collected data is then subjected to rigorous Input-Output Analysis to ensure that the mass and energy vectors are balanced in each technical unit to satisfy the physical principles of conservation [21]. The balanced data is then used to compile an Inventory Database.

Life Cycle Impact Assessment (LCIA)

Once the physical inventory is completed, the data should be transformed into environmental indicators. In this case, Life Cycle Impact Assessment (LCIA) plays the role of a scientifically grounded approach that helps to assess the compiled material and energy flows and transform them into environmental indicators by considering thousands of individual emissions vectors [22]. The transformation is carried out according to the methodology whose purpose is to assess the influence of resource extraction and emission on ecosystems, human health, and resource availability [23]. Within the ISO 14044 framework, this stage includes mandatory processes of Classification and Characterisation, which imply grouping of inventory data and estimating possible impacts on the basis of scientific mid-point or end-point indicators [24]. For a better perception of multi-category profiles, practitioners may use Normalisation and Weighting steps on an optional basis.

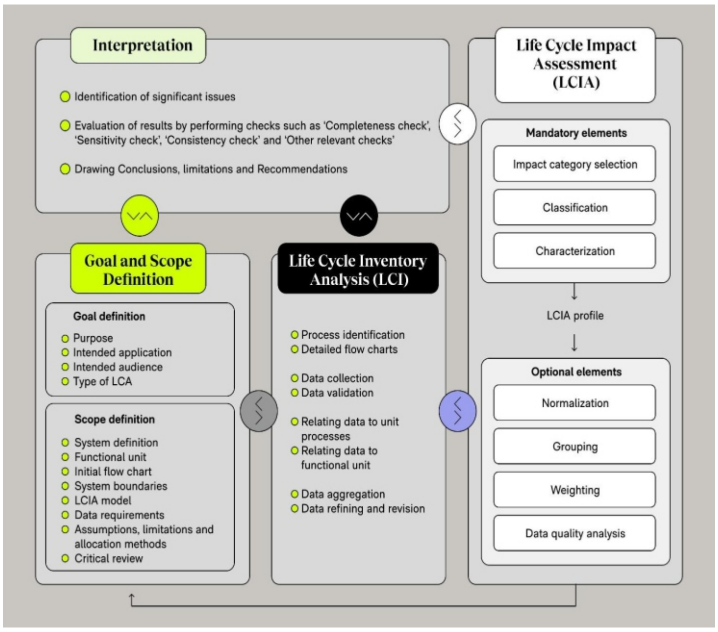

Figure 4. Steps in the life cycle impact assessment

Source: [39]

The process of evolving from the primary physical data to sustainable metrics is shown in Figure 4. Steps in Life Cycle Impact Assessment. The process begins with the gathered Inventory Data that includes all quantified amounts of resource extractions and emissions outputs produced by the product system [40].

In the Classification stage, the identified inventory flows are classified to specific Impact Categories based on the environmental effects caused by them, like methane emissions can be associated with global warming potentials, sulfur dioxide with acidification [41]. Next comes the characterisation stage, which uses characterisation factors to transform classified flows to standardised metrics [5]. This transformation results in the creation of a definite list of Environmental Indicators that gives an explicit overview of the system's environmental performance [28].

Applications of Life Cycle Assessment

The global transition toward a low-carbon energy economy relies heavily on life cycle assessment to quantify the true environmental payoffs of renewable alternatives. Evaluating energy architectures requires a comprehensive cradle-to-grave analysis, ensuring that the emissions eliminated during power generation are not overshadowed by upstream raw material extraction or downstream decommissioning impacts [42].

Solar Energy

In solar photovoltaic (PV) networks, LCA models track the environmental profile of crystal growth, silicon purification, and module assembly phases. Researchers emphasise that while solar systems produce zero emissions during active operation, substantial carbon footprints and toxic chemical burdens are concentrated in the manufacturing stage, particularly within regions dependent on coal-heavy electrical grids [7].

Wind Energy

Wind energy systems generally display some of the lowest lifecycle global warming potentials among renewable technologies, though they face distinct structural issues. LCA studies show that upstream material processing, specifically the production of structural steel for towers, concrete for foundations, and carbon-fibre composites for turbine blades, drives the vast majority of their embodied environmental impacts [8].

Hydrogen Energy

The environmental profile of hydrogen energy varies drastically depending on the primary feedstock and energy sources used for production. LCA frameworks are critical for comparing conventional steam methane reforming against water electrolysis powered by wind or solar configurations. Studies verify that "green" hydrogen systems achieve dramatic greenhouse gas reductions compared to fossil fuels, but they can trigger unintended burden-shifting in other impact categories, such as accelerated mineral resource depletion and regional water scarcity during catalyst and membrane fabrication [28].

Construction and Manufacturing

The built environment and industrial manufacturing sectors are major contributors to global resource consumption and waste generation. Applying life cycle thinking across these domains allows engineers to evaluate the long-term ecological impacts of structural designs and material choices [5].

Buildings

Building LCAs are typically split into embodied impacts (associated with raw material extraction, transport, and construction) and operational impacts (linked to heating, cooling, and electricity use over decades).

As energy grids become cleaner and buildings grow more energy-efficient during operations, the relative importance of embodied carbon has surged [11]. Practitioners utilise LCA to evaluate structural designs over 50-to-100-year lifespans, ensuring that materials selected for operational insulation do not carry prohibitive upstream manufacturing footprints.

Infrastructure

For large-scale infrastructure projects like highways, bridges, and utility systems, LCA provides a framework for analysing vast material volumes and long operational timelines. Studies often evaluate different pavement formulations, comparing conventional hot-mix asphalt with cold-recycled variants or concrete alternatives [20]. These models account for initial installation variables, ongoing maintenance cycles, and the rolling resistance impacts imposed on vehicles over decades of service.

Green Materials

The development of green building materials relies on life cycle metrics to validate alternative products, such as timber, bio-composites, and geopolymer concretes made from industrial by-products. LCA ensures that bio-based materials are sourced through sustainable forestry practices that protect carbon sinks, rather than causing deforestation or intensive chemical processing impacts [20].

Agriculture and Food Systems

Agri-food systems are fundamentally linked to regional ecosystem health, driving significant land use, water consumption, and nutrient pollution worldwide [22].

Food Production

Agricultural LCAs must account for complex, non-linear biological processes that differ sharply from predictable industrial factory settings. Inventory analyses cover direct farm emissions, such as nitrous oxide releases from fertilised soils and methane from enteric fermentation, alongside upstream inputs like synthetic fertiliser production [4]. These models help identify sustainable cultivation practices that maximise crop yields while minimising chemical runoff.

Water Use

Water footprinting within LCA quantifies both the direct volume of water consumed and the localised scarcity of the watershed being tapped. This spatial sensitivity is crucial because extracting a litre of irrigation water in an arid basin causes far greater environmental degradation than the same extraction in a water-abundant region [13].

Waste Management

Food supply chains generate massive organic waste streams, making sustainable end-of-life management a top priority. LCA is used to compare disposal options, analysing the environmental trade-offs between landfilling, anaerobic digestion for biogas recovery, and composting for nutrient cycling. These models show how diverting organic waste from landfills directly mitigates fugitive methane emissions while supporting a circular bioeconomy [15].

Table 1: Adaptive scope of life cycle assessment across environmental systems

Sector	Typical Applications	Environmental Benefits	Common Impact Categories
Energy	Solar PV manufacturing, wind farm placement, hydrogen electrolysis scaling	Lower atmospheric emissions, reduced fossil fuel dependence	Climate change, abiotic resource depletion, ozone layer depletion
Construction	Commercial green buildings, pavement design, infrastructure maintenance	Reduced embodied carbon, lower operational energy use	Primary energy demand, acidification, particulate matter formation
Agriculture	Crop cultivation optimization, livestock management, precision irrigation	Sustainable farming, reduced chemical runoff, optimized water use	Water scarcity footprint, freshwater eutrophication, land use
Manufacturing	Bio-based polymer synthesis, electronics assembly, supply-chain logistics	Higher material efficiency, minimized toxic chemical usage	Human toxicity, ecotoxicity, global warming potential
Waste Management	Mechanical recycling, organic composting, waste-to-energy systems	Closed-loop material recovery, lower methane releases	Land transformation, global warming potential, photochemical oxidant creation

Sources: [12, 20]

The cross-sector matrix presented in Table 1 illustrates how LCA adaptively scales its focus based on the distinct physical characteristics of each environmental sector. In energy and manufacturing domains, assessment models generally emphasise highly standardised, global impact categories like climate change and resource depletion, where industrial input-output data can be collected with high precision 42]. Conversely, in agriculture and construction sectors, the analytical focus shifts toward site-specific, spatially dependent impact categories such as land transformation, water scarcity, and freshwater eutrophication [12]. This variability highlights the need for flexible, multi-criteria LCIA methods that can capture both global atmospheric trends and localised ecosystem impacts across diverse industrial systems.

Challenges and Future Directions

Despite its international standardisation and widespread adoption, the practical application of LCA faces several persistent methodological and operational bottlenecks that can compromise the reliability of its outputs [14].

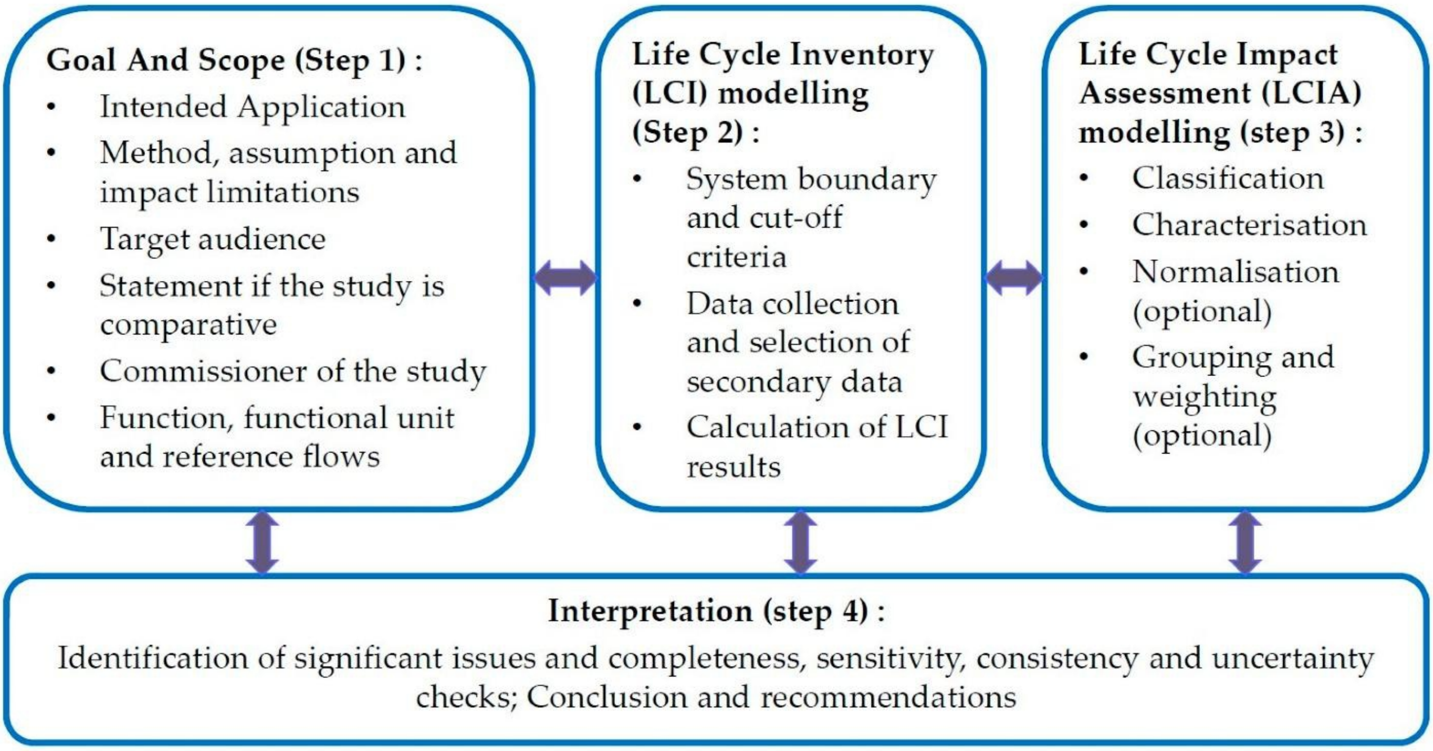

Figure 5. Major challenges affecting life cycle assessment studies

Source: [33]

Methodological limitations of LCA are strongly interrelated, as can be seen in Figure 5, where data uncertainty is depicted as a key limitation for each step of the analysis. The lack of primary industrial data and strong dependency on out-of-date background databases make it necessary to use data on various technologies or in different geographical locations for LCI creation [28, 32]. Uncertainty of inventories leads to uncertainty during the LCIA due to the use of generalisation factors that do not take into account regional environmental sensitivity, temporal changes in emissions and other location-specific conditions [30, 31].

Another challenge that is quite common in LCA involves the apportionment of environmental loads in cases where there are several co-products created from a single process within an industry. For instance, in the petroleum refinery, the co-products include gasoline, diesel, and asphalt, and in a chlor-alkali plant, both hydrogen and chlorine are produced [17]. As per ISO 14044, it is advised to avoid allocating the impacts by either expanding the system boundary or subdividing the processes, but in most cases, mass, energy, or economic allocation has been used with varying environmental consequences. Moreover, regionality has not been addressed in many LCA cases due to the fact that databases commonly used for carrying out LCA include data mainly from Europe and North America.

Emerging Trends

To resolve these historical limitations, the field of life cycle engineering is undergoing a digital transformation, leveraging advanced computing technologies to shift from static, retrospective profiles toward real-time, predictive sustainability analytics [30].

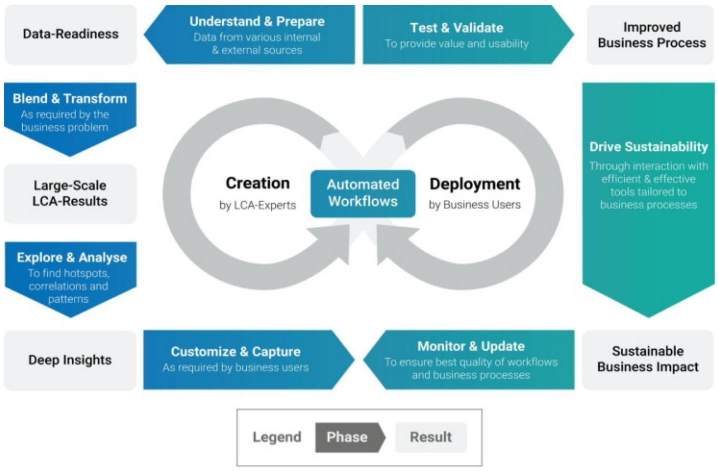

Figure 6. Future evolution of life cycle assessment

Source: [33]

The future development of LCA, shown in Figure 6, includes a shift from traditional, spreadsheet-based LCA to full-scale digital LCA systems that integrate artificial intelligence (AI), big data analytics, digital twins, and real-time environment monitoring [32]. Traditional LCA relies mostly on the inventory compilation and updating process done manually, while digital LCA provides direct connections with industrial enterprise systems to collect environmental data automatically [23]. Algorithms and machine learning models enhance the described system by providing automatic dataset cleaning, anomaly detection, inventory gap filling, and increasing the quality of life cycle inventories [4, 23].

In addition to the inventory automation process, AI helps in making predictive assessments in sustainability. Machine learning and text mining approaches are used to identify environmental information in manufacturing documentation and reports, while the predictions of greenhouse gases, toxicity, and other environmental aspects are made using deep learning models at the design phase, facilitating the eco-design decision-making process [28, 30]. Such an approach turns LCA into a framework for predicting environmental consequences rather than assessing them retrospectively [12, 14].

Combining dynamic LCA and digital twin technologies takes environmental systems analysis to the next level through consideration of the temporal dynamics of industrial production and environmental changes. In contrast to conventional LCA, which assumes constant emission levels at one particular moment in time, dynamic LCA considers varying electricity mixes, seasonality, and ecosystem reaction dynamics via time-dependent characterisation factors [23]. Combining such models with the help of IoT-based digital twins makes it possible to conduct continuous assessment of manufacturing systems, real-time sustainability evaluation, and predictive optimisation of industrial activity in order to reduce carbon footprint and resource utilisation [4, 7]. As seen in Figure 6, the combination of digital LCA, artificial intelligence, real-time analyses, and predictive decision support systems will likely change environmental assessment dramatically [20, 23].

Conclusion

It is evident that Life Cycle Assessment (LCA) is the inevitable diagnostic framework of environmental management, ecological engineering, and sustainable policymaking of the current age. Moving from site-specific mitigation solutions at the end of the pipe to a more holistic approach in terms of value chain, life cycle thinking manages to reveal unnoticed hotspots, reduce the effect of cross-media shifts of pollution and offer the quantified validation of circular economic scenarios. However, the applicability of traditional LCA methodology is restricted by the following operational difficulties: spatial-temporal aggregation mistakes, lack of information in emerging countries, and controversial approaches to the problem of co-product allocation.

Environmental systems modelling will be developed through the rapid deployment of new digital technologies. Shifting from static retrospective estimations towards real-time assessment based on artificial intelligence, big data analysis and digital twins will enable engineers and policymakers to develop prescriptive solutions based on their diagnostics. Finally, as these computational technologies become more sophisticated and standardised inventory databases become worldwide, LCA will turn into a tool of structural change that will drive industrial metabolism to resource conservation and low-carbon transition.

Authors' Contributions

The authors of this research have significantly contributed to the study's conception, data collection, and manuscript development. All authors were involved in writing the manuscript or critically reviewing it for its intellectual value. They have reviewed and approved the final version for submission and publication and accept full responsibility for the content and integrity of the work.

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Conflict of Interest

The authors declared that there are no conflicts of interest.

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